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Abstract

A polarized ^{13}C target has been developed and used to measure spin observables for 500-MeV p - ^{13}C elastic scattering. The material was ethylene glycol, $^{13}\text{C}_2\text{H}_6\text{O}_2$, enriched to 99% in ^{13}C . Both the ^{13}C and ^1H spins were dynamically polarized in a ^3He refrigerator at 2.5-T magnetic field. The polarization of both species was measured by using the NMR thermal equilibrium calibration technique. In addition, the polarization of ^1H was independently measured by p-p scattering. We describe the target and report on the polarizations obtained and the dependence of the polarizations on integrated beam intensity.

Introduction

Historically the primary effort in polarized target material development has focused on obtaining materials for polarized ^1H and ^2D targets. This selected concentration has been driven by the need to measure important spin-dependent observables for both the nucleon - nucleon and pion - nucleon programs. As the N - N interaction has become better understood, a theoretical effort has been mounted, that utilizes an effective nucleon - nucleon interaction to describe nuclear physics ($A > 2$) phenomena. Some theoretical models^{1,2} incorporating a relativistic Hamiltonian have shown that various observables involving a polarized nuclear target ($A > 2$) are important because they test the underlying assumptions of the model. As a result of this interest a polarized nuclear target program ($A > 2$) has been initiated at LAMPF.^{3,4}

The first experiment of this program, E-955², was elastic scattering of 500-MeV polarized protons from an N-type vertically polarized ^{13}C target. The High Resolution Proton Spectrometer (HRS) was used to measure two new spin observables the target analyzing power, A_{0n} , and the beam target spin correlation parameter, A_{nn} . We describe the target and report on preliminary polarization results.

^{13}C Target

The target polarization was enhanced dynamically at 2.5 T magnetic field in a ^3He refrigerator. The target material⁵ was 99 atom % ^{13}C enriched ethylene glycol, $^{13}\text{C}_2\text{H}_6\text{O}_2$, doped with the paramagnetic complex EHBA Cr(V) (7×10^{19} electrons/cm³). The material was in the form of glassy beads about 1.5 mm in diameter. The volume of the cylindrical target was 1.6 cm³ and the axis of the target was parallel to the field of a C type

electromagnet. The effective thicknesses of ^{13}C and ^1H were 280 mg/cm² and 66 mg/cm², respectively.

To keep the overall energy resolution below 1 MeV (FWHM), which was necessary to resolve the elastic peaks of protons scattered from ^{13}C and ^{16}O , the mass surrounding the target was reduced to a minimum. The only metal was the thin copper microwave cavity. A proton of 500 MeV lost most of its energy in the target material (about 1.7 MeV) and in the surrounding liquid ^3He (2.4 MeV).

An NMR coil was wound around the FEP target holder, so that the incoming and scattered particles did not interact with it. Both the ^{13}C and ^1H NMR signals were measured with this coil; the system continuously alternated between them. The proton NMR circuit was the Liverpool-type series Q-meter⁶. The small ^{13}C thermal equilibrium signal was measured with a bridge-type circuit⁷. The beam spot on the target was 5x10 mm². It was kept smaller than the cross section of the target to reduce the possibility of systematic error in determining effective target thickness. Because of this and the location of the coil, the NMR measurement was not sensitive to polarization changes caused by localized radiation damage from the high beam intensity.

Target polarization

The polarization of both nuclei was calibrated by measuring their thermal equilibrium signals near 1 K. Typical observed enhanced polarizations were for ^{13}C (+28 ± 2)% and (-29 ± 2)% and for ^1H (+81 ± 2)% and (-83 ± 2)%.

NMR was also used to check whether or not the equal spin temperature (EST) assumption⁸ was valid. For these spin-1/2 nuclei the polarization can be expressed in terms of an effective spin temperature (T_s),

$$P = \tanh(\mu B/k_B T_s), \quad (1)$$

where μ is the nuclear magnetic moment, B is the field in which the dynamic cooling takes place and k_B is the Boltzmann constant. In Fig. 1 is shown the inverse nuclear-spin temperatures of ^{13}C and ^1H versus time during a polarization enhancement. The spin temperatures were calculated using eq. (1).

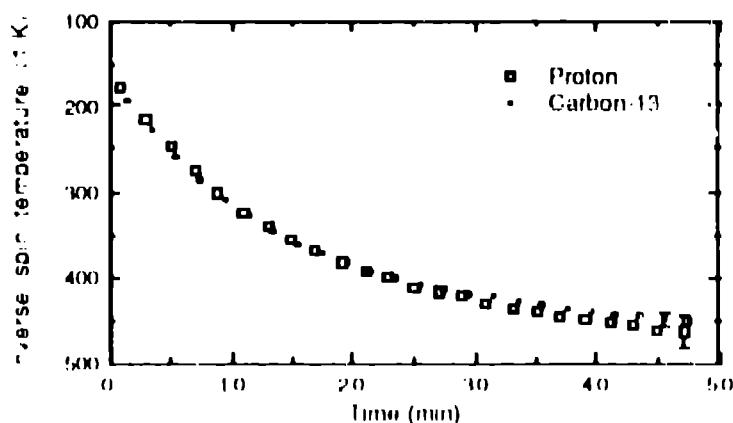


Fig. 1 The evolution of T_s^{-1} for ^{13}C and ^1H as deduced from the polarization values during a polarization enhancement

The spin-lattice relaxation times (T_1) for both nuclei were also measured at 1 K and found to be close to each other, as expected if EST holds. To within the accuracy of the NMR measurements ($\pm 2\%$), we conclude from the results of the spin-lattice relaxation and polarization enhancement measurements that EST is valid for this material.

The ^1H polarization was independently measured and monitored during the course of the experiment by using p-p elastic scattering polarimeter. An independent measurement was possible since A_{on} , and A_{nn} for p-p elastic scattering have been accurately measured in previous experiments. For this experiment measured p-p scattering asymmetry and known A_{on} and A_{nn} allow us to calculate target proton polarization. The monitor system consisted of two detector arms made up of wire chambers and scintillators. The arms detected the forward-scattered high-momentum proton in coincidence with the conjugate lower momentum proton at 46° c.m. For some angles the HRS was also used to determine the proton target polarization and calibrate the target polarimeter.

In Fig. 2 is presented the effect of the beam-induced radiation damage on the target-proton polarization as measured by the target polarimeter. The data were after the fourth annealing, which was done when 1.4×10^{14} protons/cm 2 had gone through the target. For these data only about 15% of the monitor events have been analyzed.

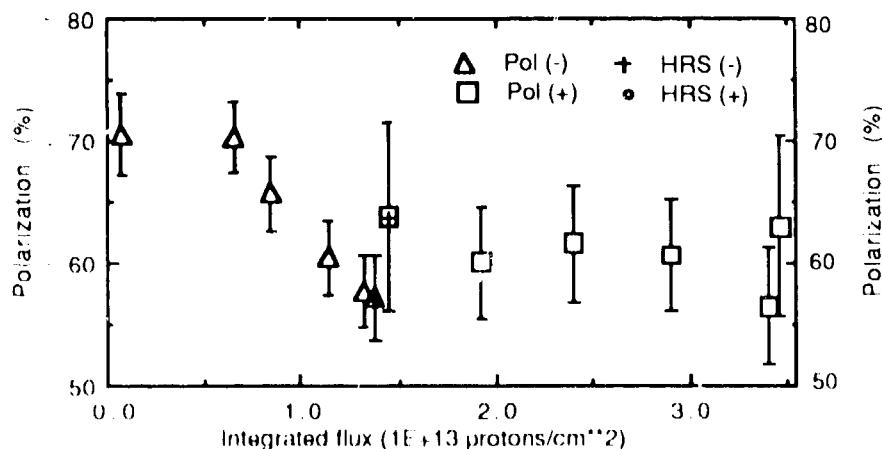


Fig. 2. Proton polarization dependence on integrated beam on the target. The polarization has been measured with the p-p target polarimeter. Two HRS measurements are also shown.

Fig. 3 shows how insensitive the NMR measurement was to changes in the target polarization when compared to that measured by p-p scattering. The data points were obtained by averaging the p-p scattering data or NMR data over 30 minute time intervals. The monitor data have not been normalized to HRS. With slightly irradiated (0.9×10^{13} protons/cm 2) material, the NMR and HRS measurements agree still within errors. The agreement of these two totally independent measurements substantiates the credibility of using NMR to determine target polarization. The fact that the NMR results disagree with the scattering data when radiation damage is present demonstrates that a serious systematic error is possible under

these conditions. One method of possibly reducing this error would be to imbed the NMR coil directly in the material where the beam interacts. However, when an effort is made to perform as accurate an experiment as practical, these results imply that a nuclear scattering measurement, independent of NMR, should be employed. For the present experiment, the target ^1H polarization was measured by p-p scattering, and since EST has been demonstrated as valid, the ^{13}C polarization can be obtained.

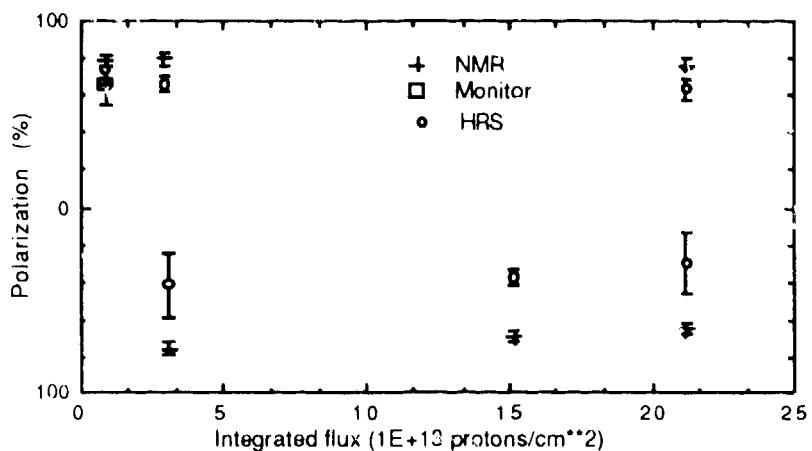


Fig. 3. Proton polarization dependence on integrated beam measured with the NMR, p-p target polarimeter, and HRS.

Radiation resistivity of $^{13}\text{C}_2\text{H}_6\text{O}_2$

The flux of 500-MeV protons was measured with an ion chamber downstream of the target. The experiment typically ran with a beam current of 5 to 30 pA depending on the scattering angle. This is a relatively high beam intensity for a solid-state polarized target. The intense beam caused radiation damage and decay of the polarization. The polarization could be restored by annealing. This was done by warming the material to 180 K for about a minute. After seven annealings the material was changed.

If we assume that the polarization decay obeys the simple form⁹

$$p(\phi) = p_0 \exp(-\phi/\phi_0), \quad (2)$$

where $p(\phi)$ is the polarization after irradiation with ϕ protons per cm^2 , p_0 is the initial polarization, and ϕ_0 is the characteristic flux for polarization to decrease by $1/e$; then from the p-p target polarimeter data, ϕ_0 can be extracted. We obtained for the positive and negative polarization,

$$\phi_0(+)= (2.0 \pm 0.6) \times 10^{14} \text{ protons/cm}^2,$$

$$\phi_0(-)= (8.0 \pm 0.2) \times 10^{13} \text{ protons/cm}^2.$$

In Table 1 the dependence of the spin lattice relaxation times (T_1) on the total proton flux on the target is presented. These times have been calculated from NMR measurements at 1 K and field of 2.5 T. The technique used was to slightly enhance the polarization with microwaves and then measure the polarization decay to its thermal equilibrium.

Table 1.
Spin-lattice relaxation times at 1 K and 2.5 T vs proton flux.

Pol	$T_1(^1\text{H})(\text{min})$	$T_1(^{13}\text{C})(\text{min})$	Flux (10^{13} protons/cm 2)
-	7.9	8.2	0
-	8.2	8.1	≈ 1
-	7.3	7.3	$\approx 1 (*)$
+	9.2	9.3	$\approx 1 (*)$

(*) after 7th annealing when the total flux was 1×10^{14} protons/cm 2 .

To explain the difference in the characteristic radiation fluxes $\phi_0(+)$ and $\phi_0(-)$ as well as relaxation times $T_1(+)$ and $T_1(-)$ without electron paramagnetic resonance measurements is difficult. One can postulate that the g-factor of the radiation-produced radicals (paramagnetic centers) is larger than that of Cr(V). As a result, they overlap asymmetrically so that they do not equally influence both enhancements. This type of an effect has been reported in alcohol-based target materials⁹.

Conclusion

The success of the polarized ^{13}C target used for E-955 has demonstrated the feasibility of developing polarized nuclear targets for use in medium energy research. EST between ^{13}C and ^1H is a valid assumption for ethylene glycol target material. The characteristic flux of protons for polarization to decrease by 1/e in this material is for positive enhancement $(2.0 \pm 0.6) \times 10^{14}$ protons/cm 2 and for negative enhancement $(8.0 \pm 0.2) \times 10^{13}$ protons/cm 2 . Care must be taken when using NMR to measure the target polarization when high beam intensity and small beam size a.e used or a systematic error may be introduced.

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